Bound on a flux of ultra-high energy neutrinos in a scenario with extra dimensions

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Plan of the talk

- Diffuse flux of cosmic neutrinos
- Neutrino events at the Pierre Auger Observatory (PAO)
- Scenario with flat extra dimensions
- Neutrino-nucleon scattering in the ADD model
- Bound on diffuse flux of ultra-high energy (UHE) neutrinos
- Expected number of neutrino events at the PAO
- Conclusions

Detection of signals from cosmic UHE neutrinos will allow:

- *to discover cosmic rays (CR) point sources*
- *to define their position, in particular, to constrain the position of the GW sources*
- *to understand mechanisms of CR acceleration*
- *to give information on the nature of the primaries*
- *to define energy boundary between galactic and extragalactic parts of CR spectrum*
- *to measure cosmic neutrino flux, flavor ratio, and UHE neutrino-nucleon cross section*

Diffuse flux of cosmic neutrinos

“Guaranteed” cosmogenic neutrino flux

$p + \gamma_{CMB} \rightarrow n + \pi^+$ $\pi^+ \rightarrow \mu^+ + \nu_\mu$ $\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$

Flavor ratio: $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$

After oscillation: $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$

Benchmark WB bound on neutrino production in optically thin sources (single flavor, 10^{13} eV < E_ν < 10^{20} eV)

(Waxman & Bahcall, PRD 64 (2001) 023002)

$$E_\nu^2 \frac{dN}{dE_\nu} = 2.33 \times 10^{-8} \mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$$

Neutrino detector IceCube: first observation of astrophysical neutrinos in the range 6.3 TeV-980 TeV

(IceCube Collab., PRL 113 (2014) 101101)

IceCube diffuse neutrino flux
(single flavor, 25 TeV< E_ν < 1.4 PeV)

(1PeV = 10^{15} eV)

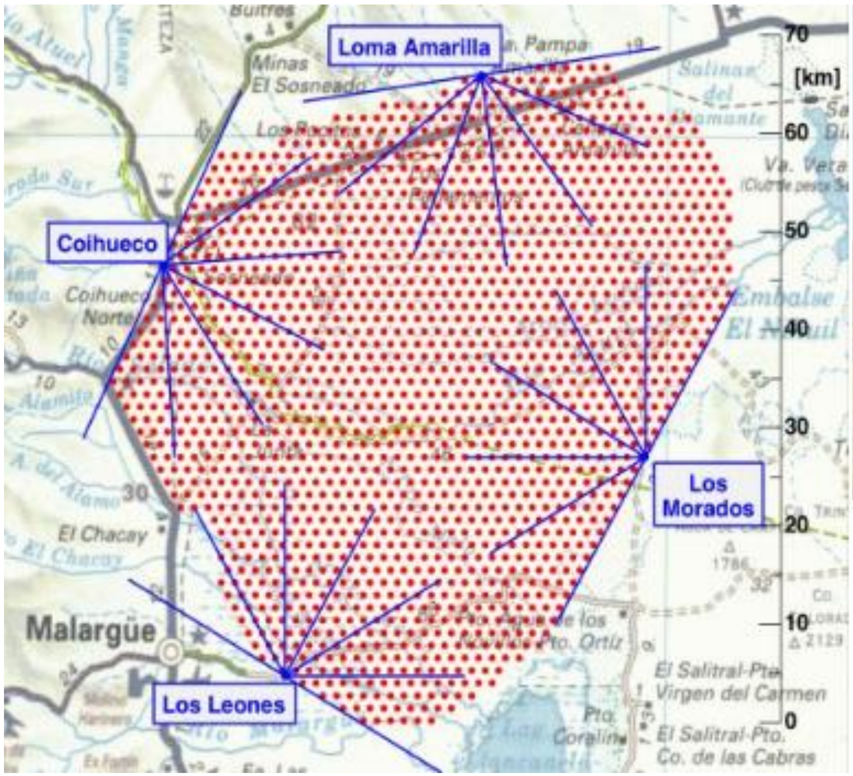
(IceCube Collab., PRD 91 (2015) 022001)

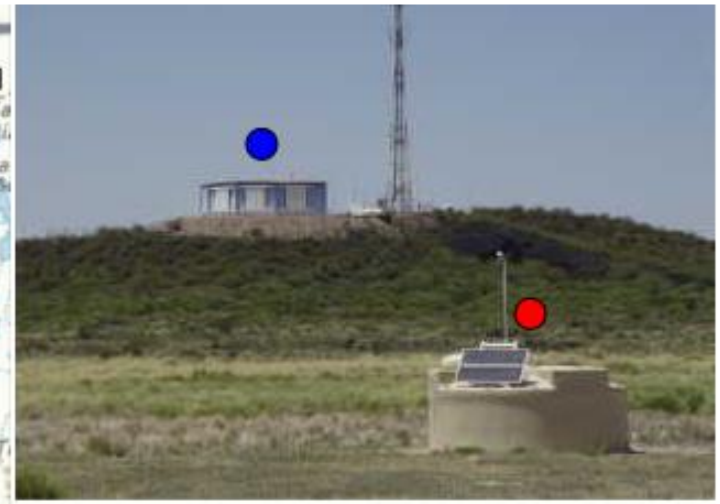
$$\frac{dN}{dE_\nu} = 2.06 \times 10^{-18} (E_0/E_\nu)^\gamma \mathrm{GeV}^{-1} \mathrm{cm}^{-2} \mathrm{s}^{-1} \mathrm{sr}^{-1}$$

$$E_0 = 10^5 \,\mathrm{GeV}, \quad \gamma = 2.46$$

(flux is consistent with the WB bound)

Pierre Auger Observatory (PAO)

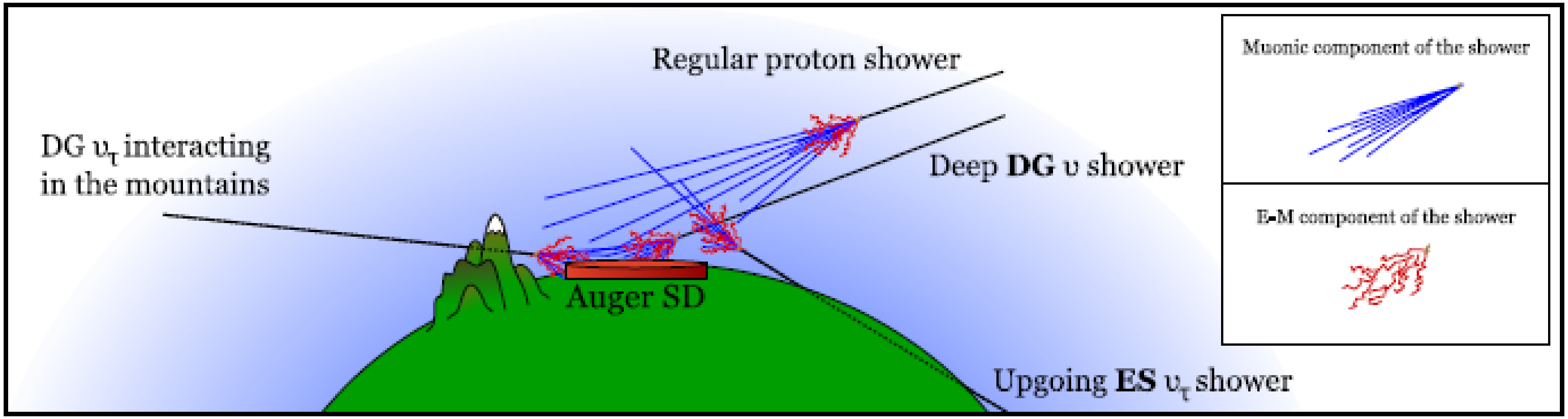




- set of fluorescence telescopes
- Cherenkov detector

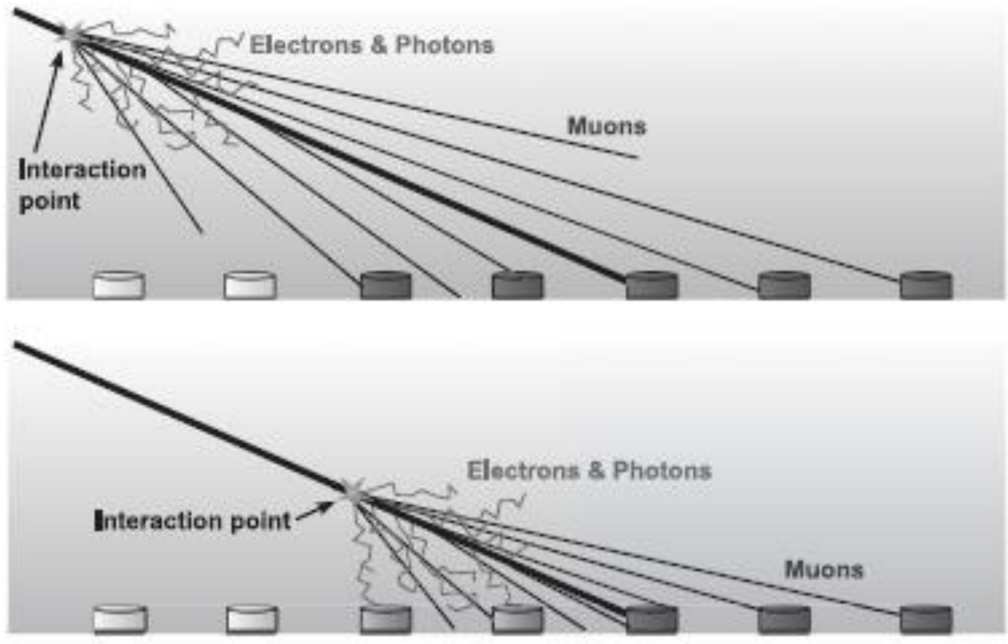
Surface Detector (SD) array: 1600 water-Cherenkov detectors spread over an area of 3000 km^2 (a bit larger than the country of Luxemburg)

Two types of UHE neutrino induced air showers at the Pierre Auger Observatory



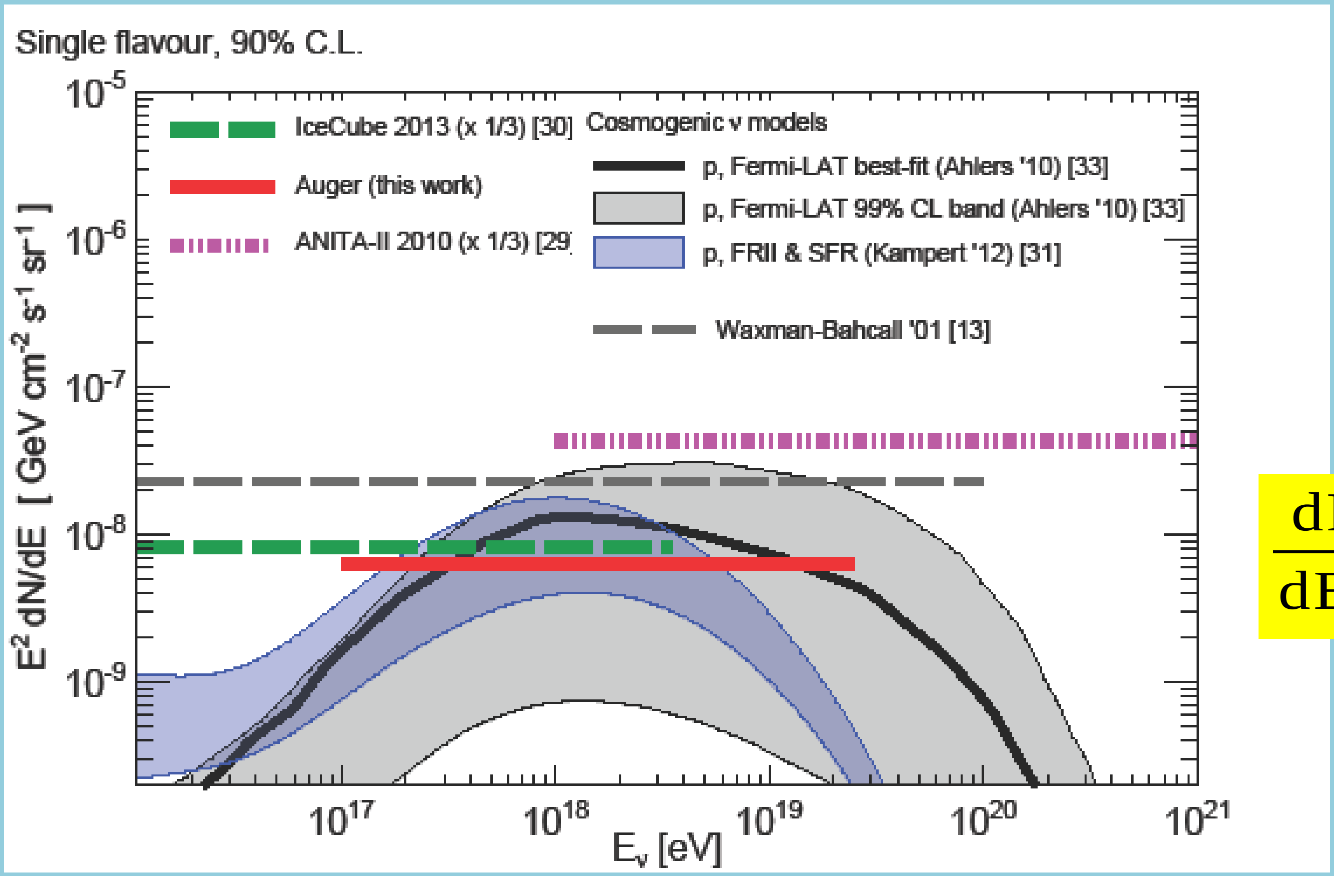
Downward-going high zenith angle (DG) and up-going Earth-skimming (ES) neutrinos

Inclined showers (with zenith angle 75°-90°) are initiated by cosmic neutrinos, not by protons(nuclei)



Inclined shower induced by hadronic interactions high in the atmosphere (upper panel) and deep inclined shower (lower panel)

(*PAO Collab. PRD 84 (2011) 122005*)



$$\frac{dN}{dE_\nu} = k \times E_\nu^{-2}$$

Upper limit to the normalization of the diffuse flux of UHE neutrinos from the PAO (red line), along with fluxes in several cosmogenic models (with protons as primaries)

(PAO Collab., PRD 91 (2015) 092008)

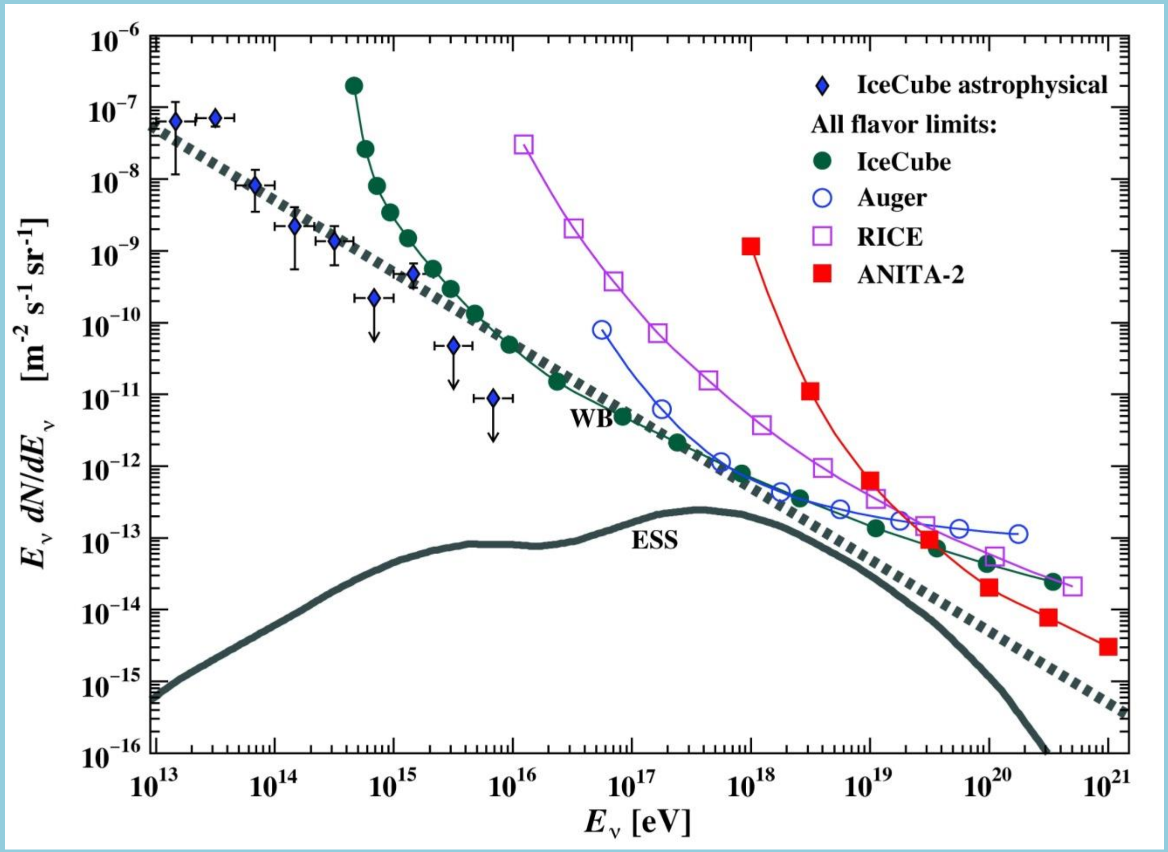
Single-flavor limit to diffuse flux of UHE neutrinos from PAO (10^{17} eV < E_ν < 2.5 $\cdot 10^{19}$ eV)

(PAO Collab., PRD 91 (2015) 092008)

$$E_\nu^2 \frac{dN}{dE_\nu} < 6.4 \cdot 10^{-9} \mathrm{GeVcm^{-2}s^{-1}sr^{-1}}$$

IceCube diffuse neutrino flux if extrapolated to 1 EeV (10^{18} eV)

$$E_\nu^2 \frac{dN}{dE_\nu} = 0.3 \times 10^{-9} \mathrm{GeVcm^{-2}s^{-1}sr^{-1}}$$



The best-fit IceCube astrophysical all-flavor neutrino flux

(PDG, Chin. Phys. C, 40 (2016) 100001)

Mergers of black holes are potentially environment for accelerating CRs to ultra-high energies

UHECRs can interact with the surrounding matter or radiation to produce UHE gamma rays and neutrinos

(Kotera and Silk, Astr. J. Lett. (2016) 823)

PAO: no neutrinos from the GW sources

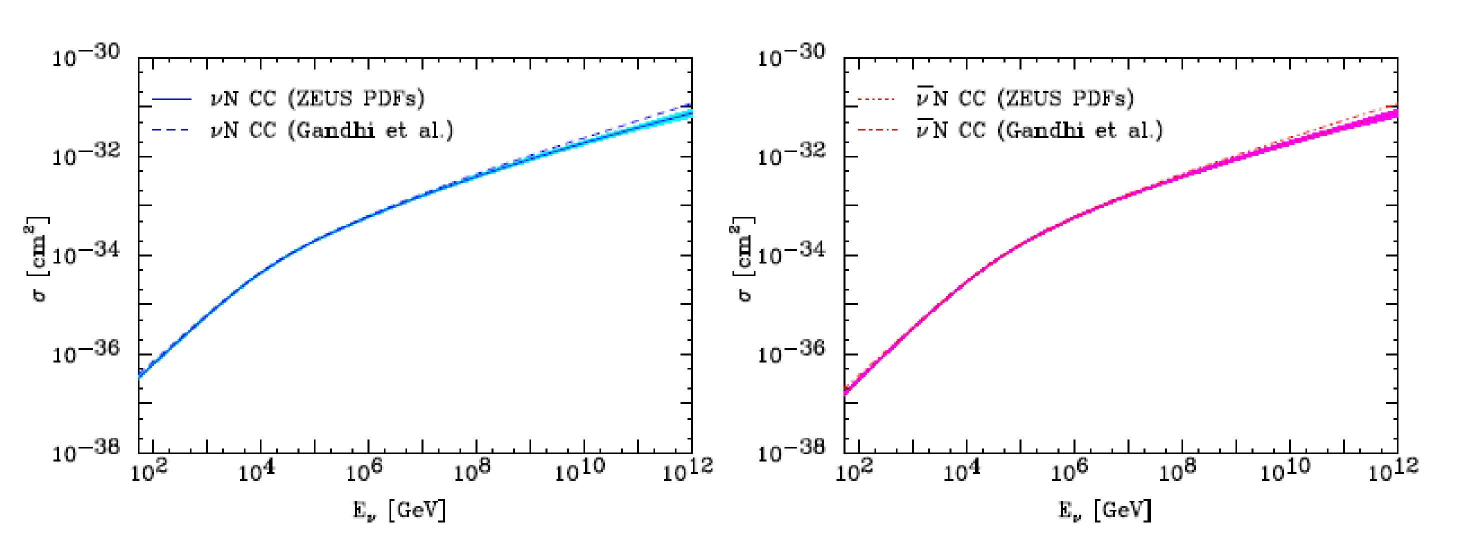
(PAO Collab., PRD 94 (2016) 122007)

Upper bound on the diffuse single-flavor flux integrated over population of GW sources

(Kotera and Silk, Astr. J. Lett. (2016) 823)

$$E_\nu^2 \frac{dN}{dE_\nu} = (1.5 - 6.9) \times 10^{-8} \,\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$$

SM: $\sigma_{\nu N}$ is small and rises slowly with energy



The total CC cross sections for neutrinos (left figure) and antineutrinos (right figure)

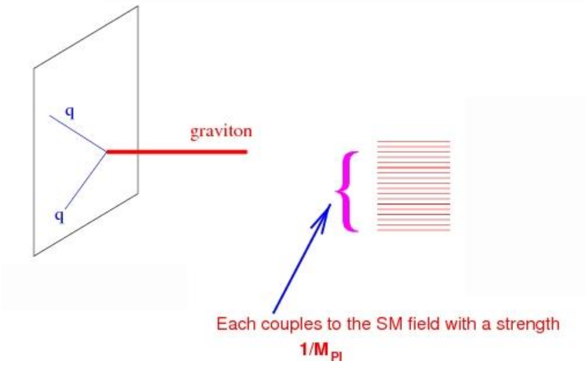
(Cooper-Sarkar & Sarkar, JHEP 080 (2008) 075)

Significant (dominating) contribution from "new physics" is expected at ultra-high neutrino energies

Scenario with large flat extra dimensions (ADD model)

(Arkani-Hamed, Dimopoulos and Dvali, Antoniadis, 1998)

Parameters of the model: number of extra dimensions n (D=4+n), D-dimensional gravity scale M_D, compactification radius R_c



Hierarchy relation: $$M_{\rm Pl}^2 = (2\pi R_c)^n M_D^{n+2}$$

Masses of KK gravitons: $$m_n = n/R_c$$

Interaction Lagrangian on the brane: ***(massive gravitons only)***

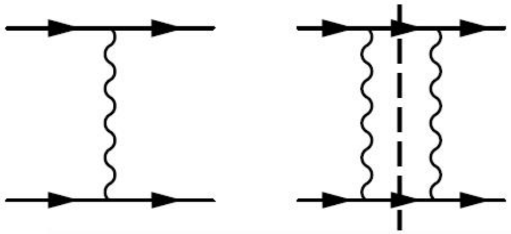
$$L(x) = -\frac{1}{\overline{M}_{\rm Pl}} \sum_{n=1}^{\infty} h_{\mu\nu}^{(n)}(x) T^{\mu\nu}(x)$$

Scattering of UHE neutrinos in ADD model

Transplanckian region

$$E_\nu > 10^{17}\,\text{eV},\ \sqrt{s} >> M_D, -t$$

Sum of the ladder diagrams in the eikonal approximation. Wavy lines represent the exchange of *D*-dimensional gravitons



Scattering amplitude in the eikonal approximation

$$A_{\text{eik}}(s,t) = -2is\int_0^\infty db\, b J_0(b\sqrt{-t})\{1-\exp[i\chi(s,b)]\}$$

$$-t = q^2$$

Eikonal scattering phase

$$\chi(b) = \frac{1}{2s}\int \frac{d^2q}{(2\pi)^2}\, e^{iqb} A_{\rm Born}(q^2)$$

$$\chi(b) = \left(\frac{b_c}{b}\right)^n \qquad b_c = \left(\frac{(4\pi)^{n/2-1} s\Gamma(n/2)}{2M_D^{n+2}}\right)^{1/n}$$

(Giudice, Rattazzi and Wells, Nucl. Phys. B 630 (2002) 293)

$$q << b_c^{-1}, \quad \frac{d\sigma_{\rm eik}}{dt} \sim \frac{\sigma_{\rm BH}}{s}\left(\frac{s}{M_D^2}\right)^{\frac{(n+2)^2}{n(n+1)}} \qquad q >> b_c^{-1}, \quad \frac{d\sigma_{\rm eik}}{dt} \sim \frac{\sigma_{\rm BH}}{s}\left(\frac{s}{-t}\right)^{\frac{n+2}{n+1}}$$

Geometric black-hole cross section

$$\sigma_{\rm BH} = \pi R_S^2 \qquad R_S \sim \left(\frac{\sqrt{s}}{M_D^{n+2}}\right)^{1/(n+1)}$$

D-dimensional Planck scale:

$$G_D = \frac{(2\pi)^{n-1}\hbar^{n+1}}{4c^{n-1}M_D^{n+2}}$$

Planck length:

$$\lambda_{\mathrm{Pl}} = \left(\frac{G_D\hbar}{c^3}\right)^{\frac{1}{n+2}}$$

Quantum gravity effects become important at distances below λ_{Pl}

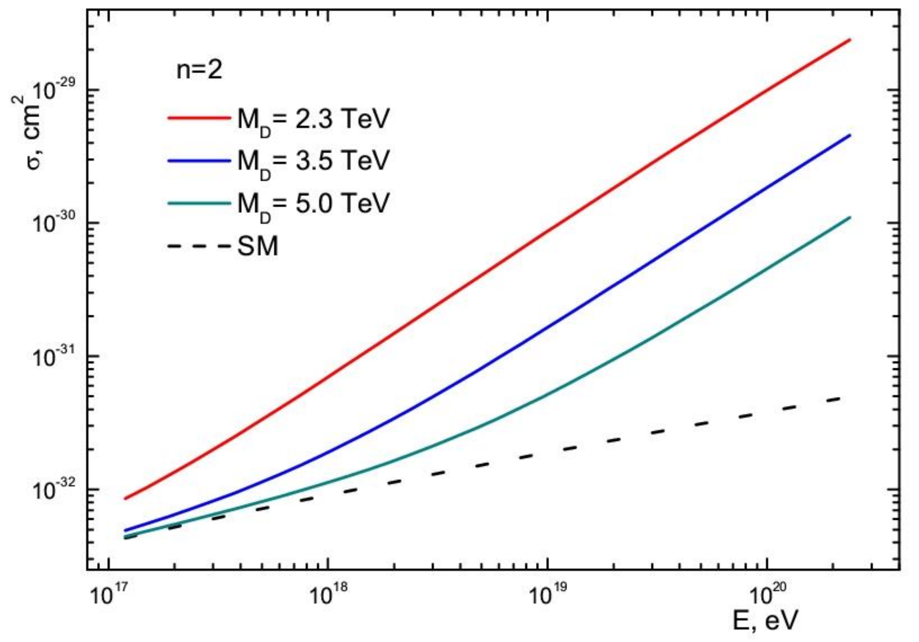
In the limit $\hbar \to 0$, with G_D and $\sqrt{s}$ fixed, M_D vanishes

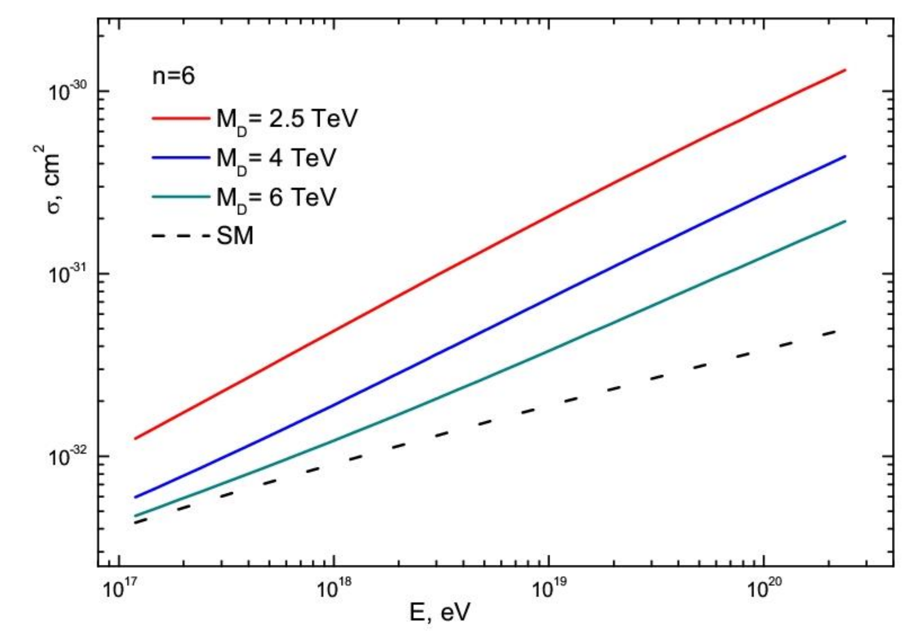
Transplanckian regime corresponds to a classical limit (b > R_S)

$$\sqrt{s} >> M_D,\ \ R_S >> \lambda_{\mathrm{Pl}},\ \ \theta \sim (R_S / b)^{n+1}$$

b < R_S → **black hole production**

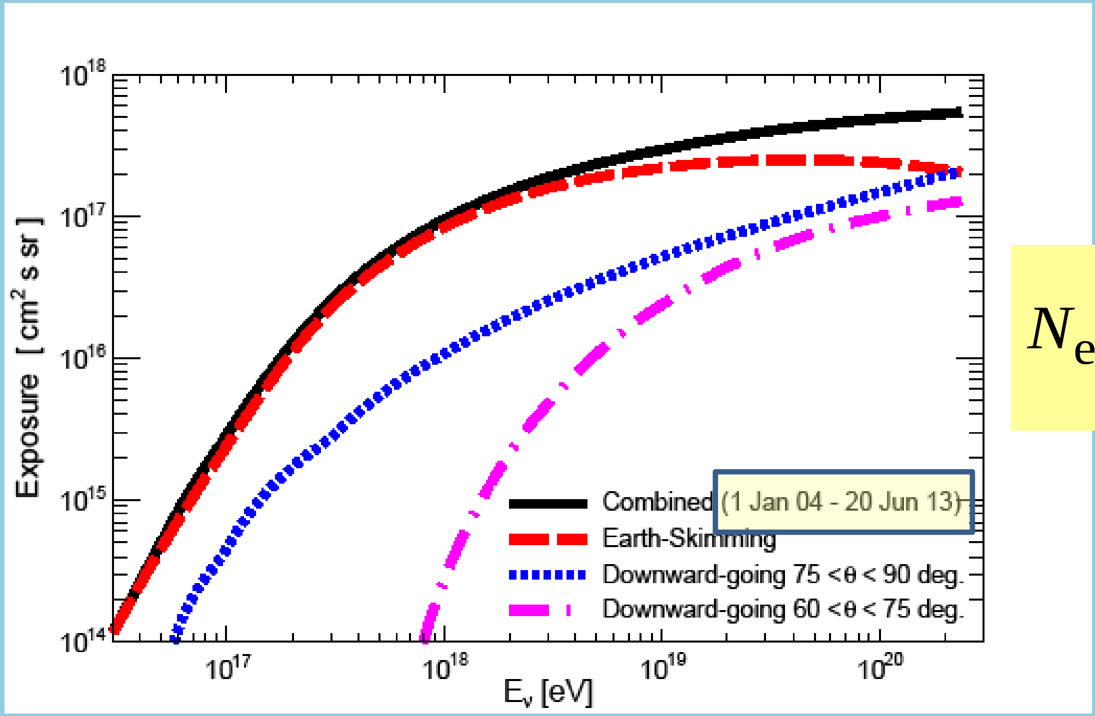
BSM: $\sigma_{\nu N}$ rises more rapidly than in SM as neutrino energy grows





The total neutrino-nucleon cross sections for **n=2** (left panel) and **n=6** (right panel) with different values of the gravity scale $\mathbf{M_D}$

Exposures of the SD array of the Pierre Auger Observatory



$$N_{\text{ev}} = \int \frac{dN}{dE_\nu} \mathcal{E}(E_\nu) dE_\nu$$

Exposures of the SD of the PAO for the period equivalent to 6.4 years of continuous operation as a function of the neutrino energy
(PAO Collab., PRD 91 (2015) 092008)

DG neutrinos: enhanced interaction cross-section increases exposure:

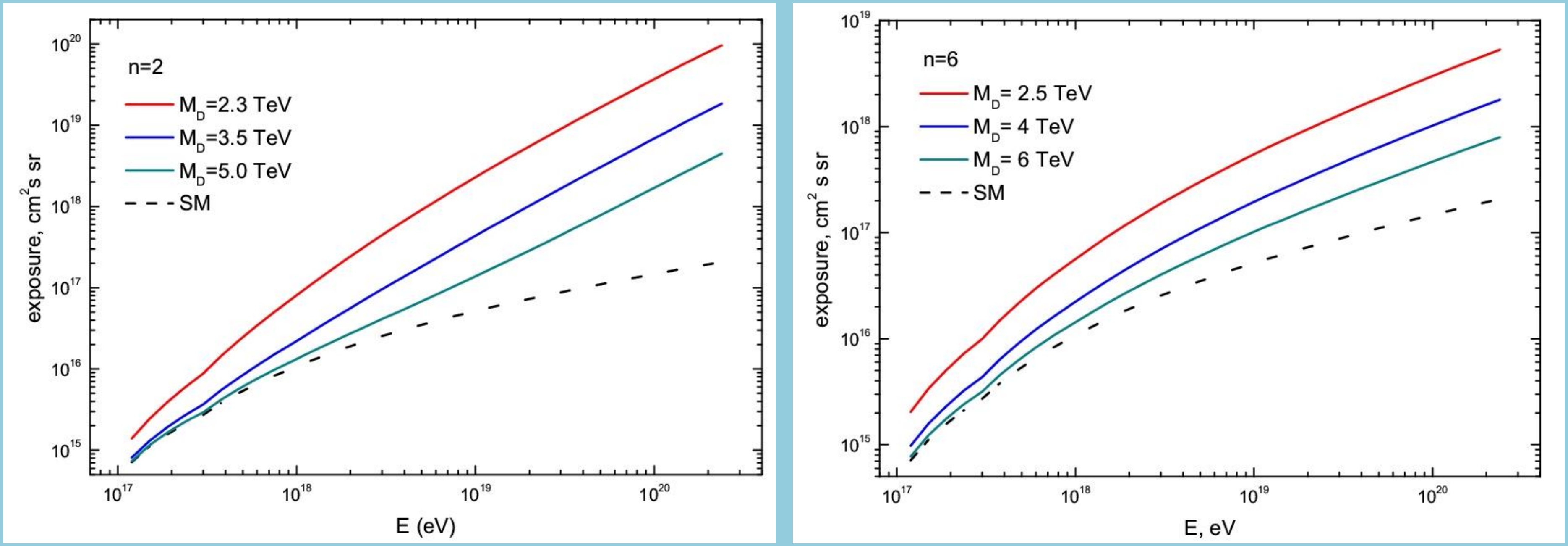
$$\varepsilon_{BSM}^{DG} = \varepsilon_{SM}^{DG} \frac{\sigma_{SM} + \sigma_{BSM}}{\sigma_{SM}}$$

ES neutrinos: enhanced interaction cross-section suppresses exposure:

$$\varepsilon_{BSM}^{ES} = \varepsilon_{SM}^{ES} \left(\frac{\sigma_{CC}}{\sigma_{CC} + \sigma_{BSM}} \right)^2$$

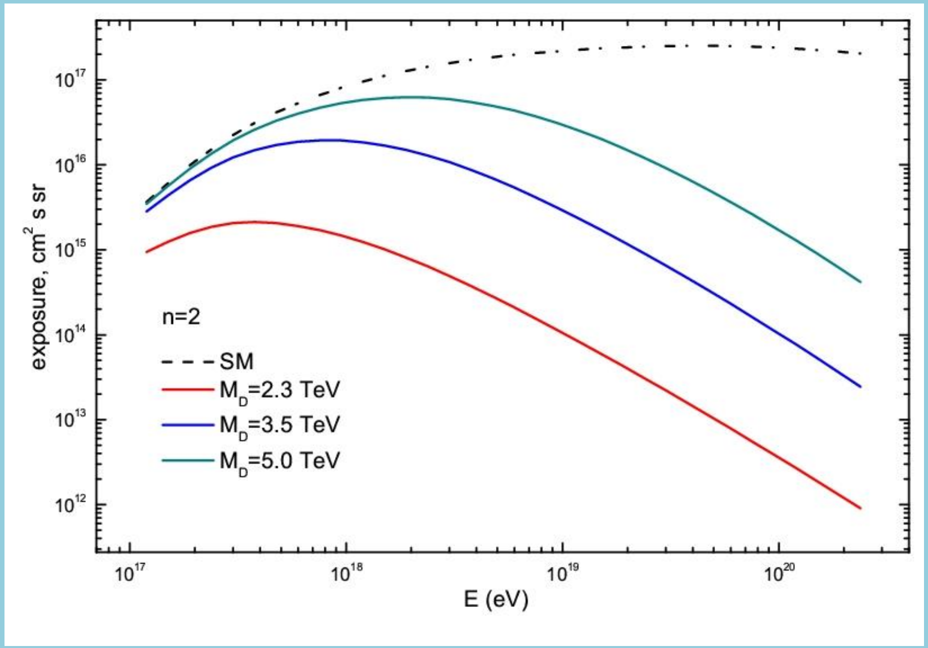
(Anchordoqui et al, PRD 82 (2010) 043001)

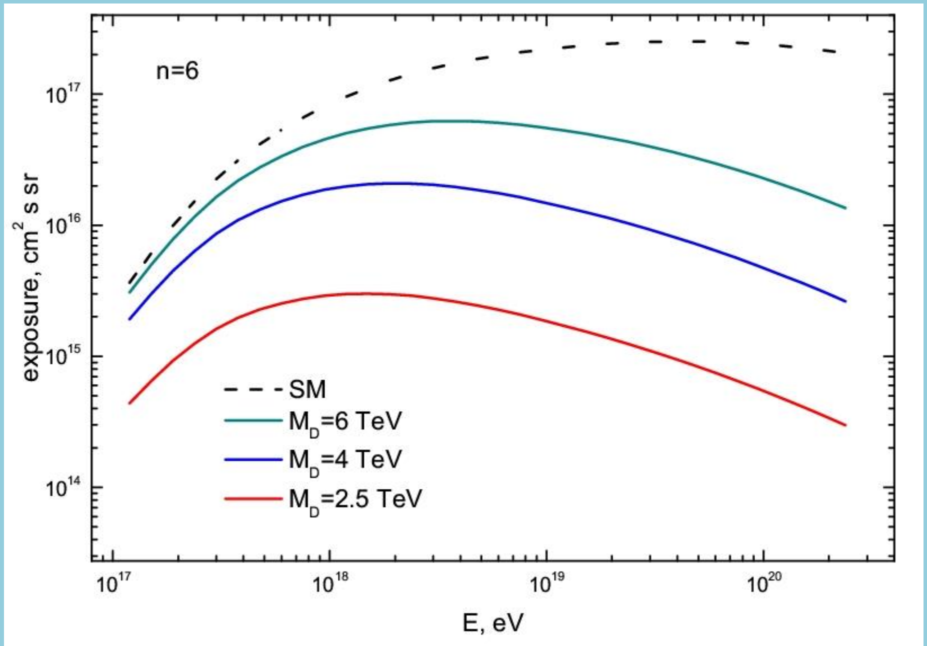
Exposures of the down-ward neutrino events in the ADD model



The exposures for the SD array of the PAO for the DG neutrino events with zenith angle **75° < θ < 90°** for different values of the gravity scale $\mathbf{M_D}$. Left panel: **n=2**. Right panel: **n=6**.

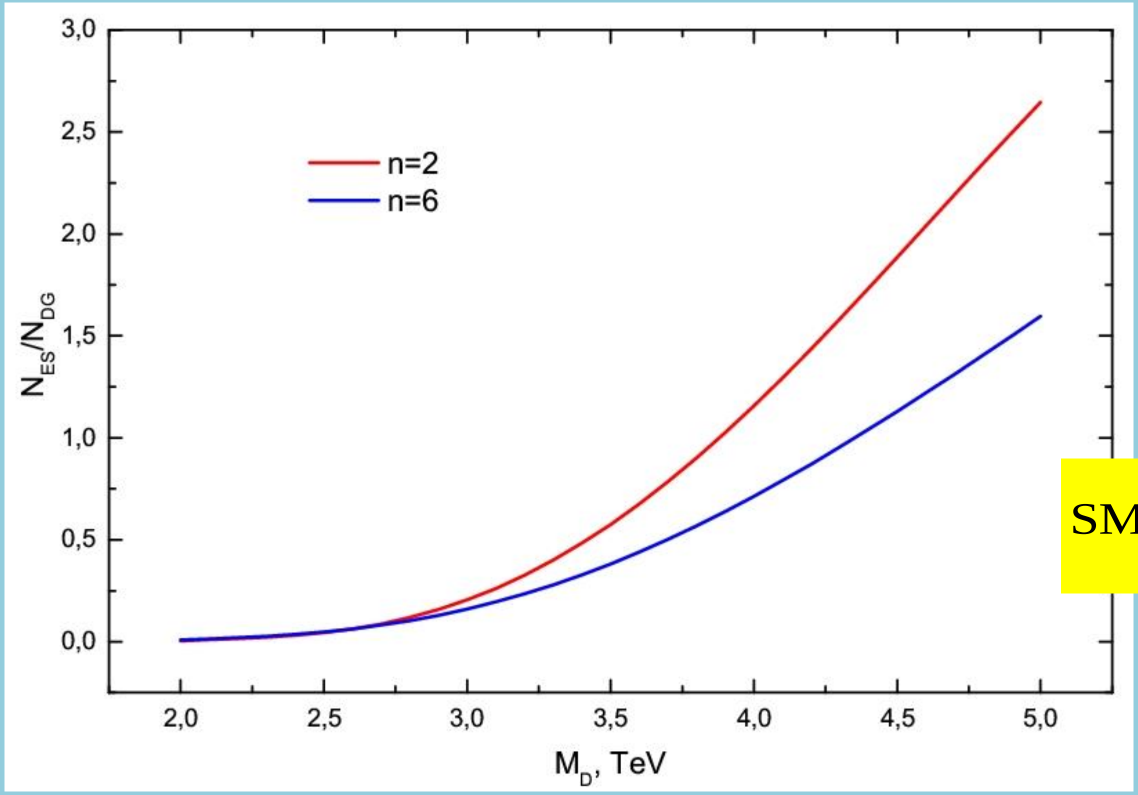
Exposures of the Earth-skimming neutrino events in the ADD model





The exposures for the SD array of the PAO for the ES neutrino events for different values of the gravity scale $\mathbf{M_D}$. Left panel: **n=2**. Right panel: **n=6**.

Numbers of down-ward and Earth-skimming neutrino events depend quite differently on $\sigma_{\nu N}$



$$\text{SM: } \frac{N_{ev}(ES)}{N_{ev}(DG)} \approx 6$$

(PAO Collab., 2015)

The expected ratio of the ES events to the DG events (with zenith angle **$75° < \theta < 90°$**) at the SD array of the PAO as a function of **M_D** and **n.**

Bound on diffuse flux of UHE neutrinos

Diffuse neutrino flux: $$\frac{dN}{dE_\nu} = k\,E_\nu^{-2}$$

- number of observed events = 0

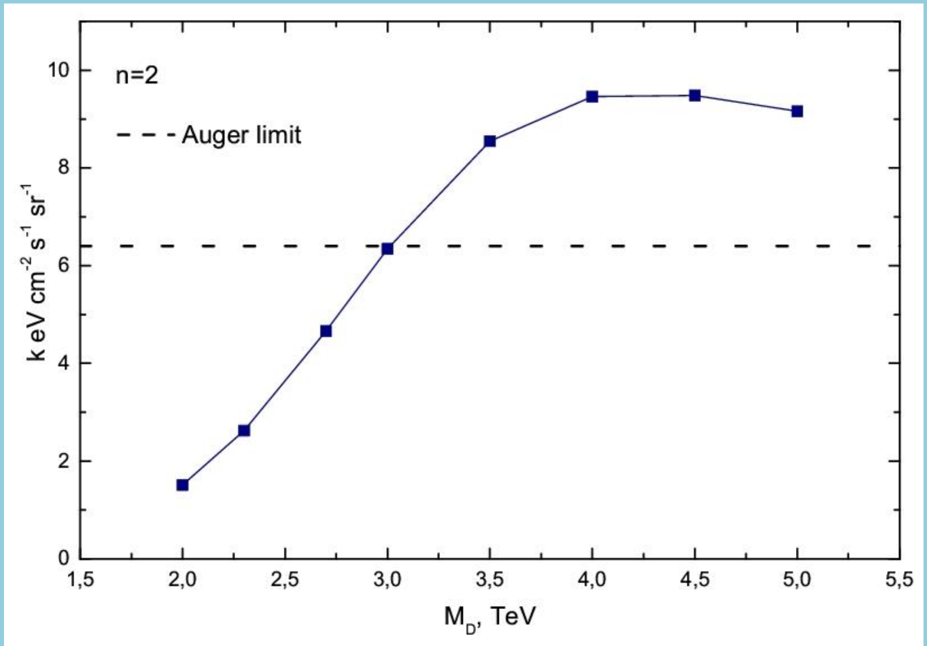
- number of expected background events = 0

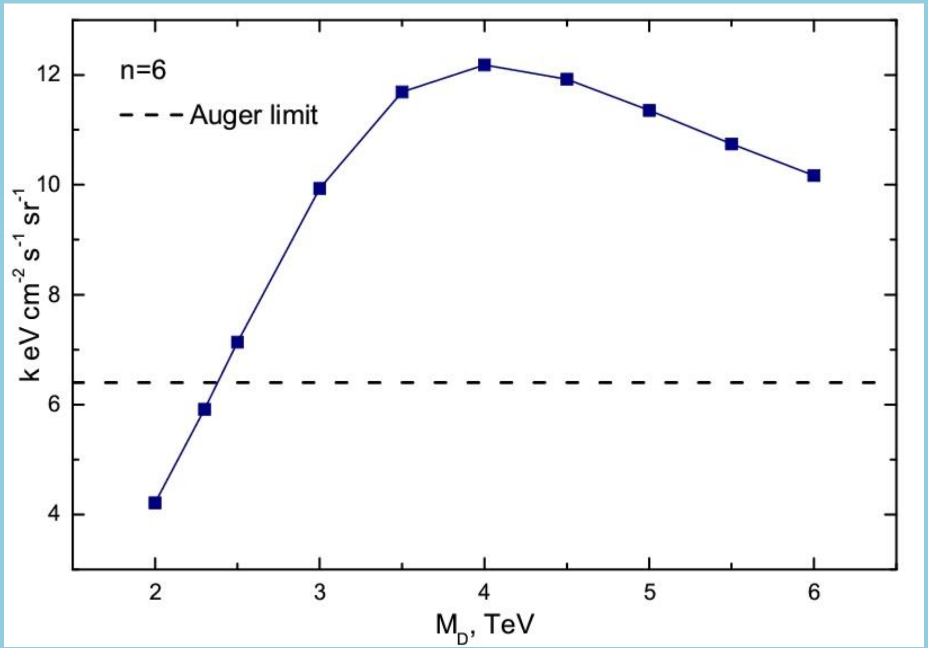
➡ **Upper limit on signal events:** $$N_{\rm up} = 2.39$$

Upper limit on k: $$k = \frac{N_{\rm up}}{\int \mathcal{E}(E_\nu) E_\nu^{-2} dE_\nu}$$

(PAO Collab., PRD 91 (2015) 092008)

Upper limit on diffuse neutrino flux in comparison with the PAO upper limit



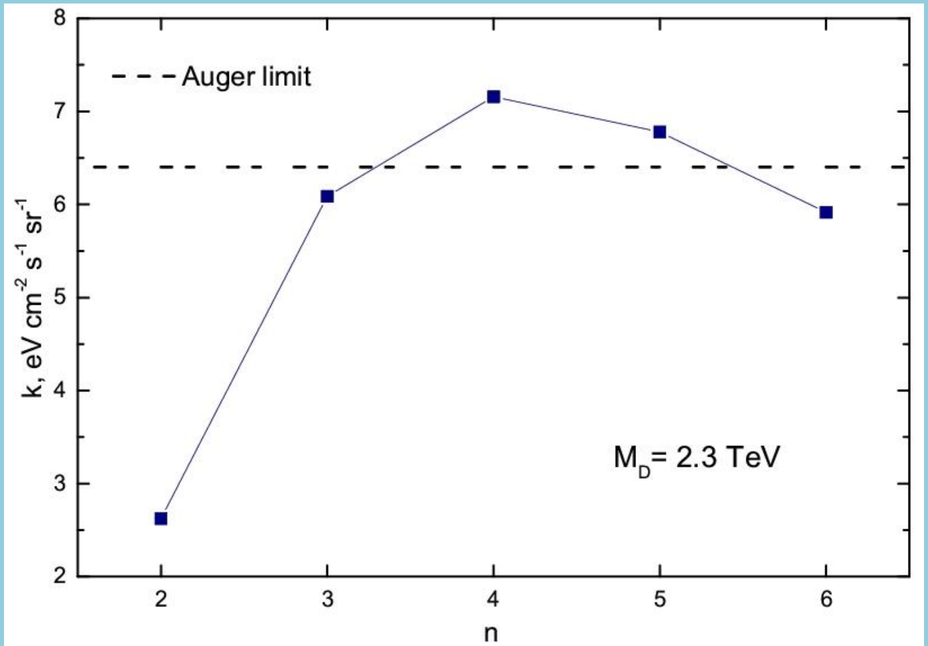


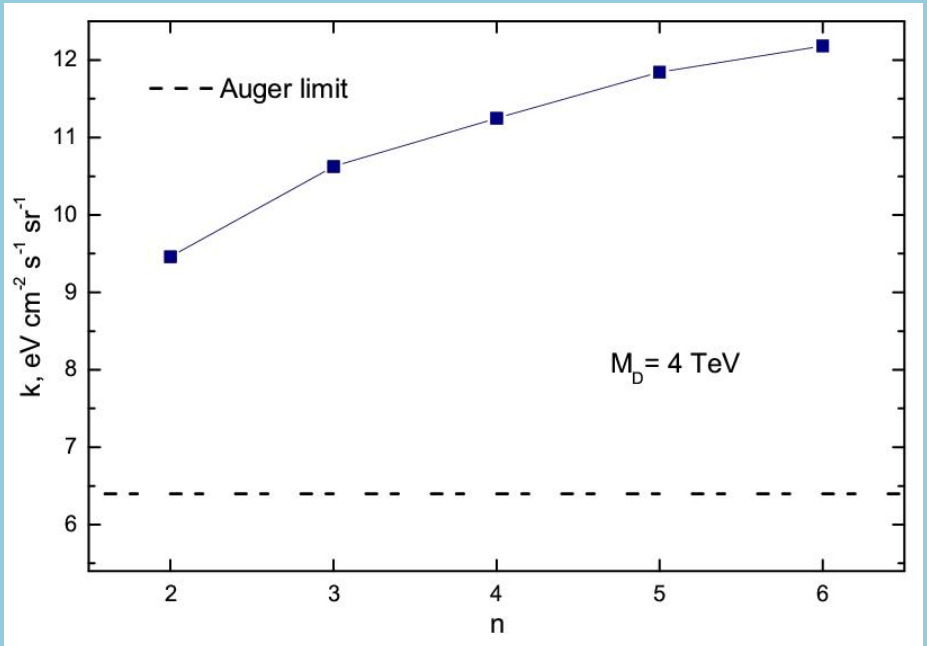
The upper bound on the flux normalizaion **k** in the ADD model as a function of $\mathbf{M_D}$ at fixed values of **n**

(M. Astashenkov and A. K., arXiv:1804.02351)

$$\frac{dN}{dE_\nu} = k \times E_\nu^{-2}$$

Upper limit on diffuse neutrino flux: nontrivial dependence on n

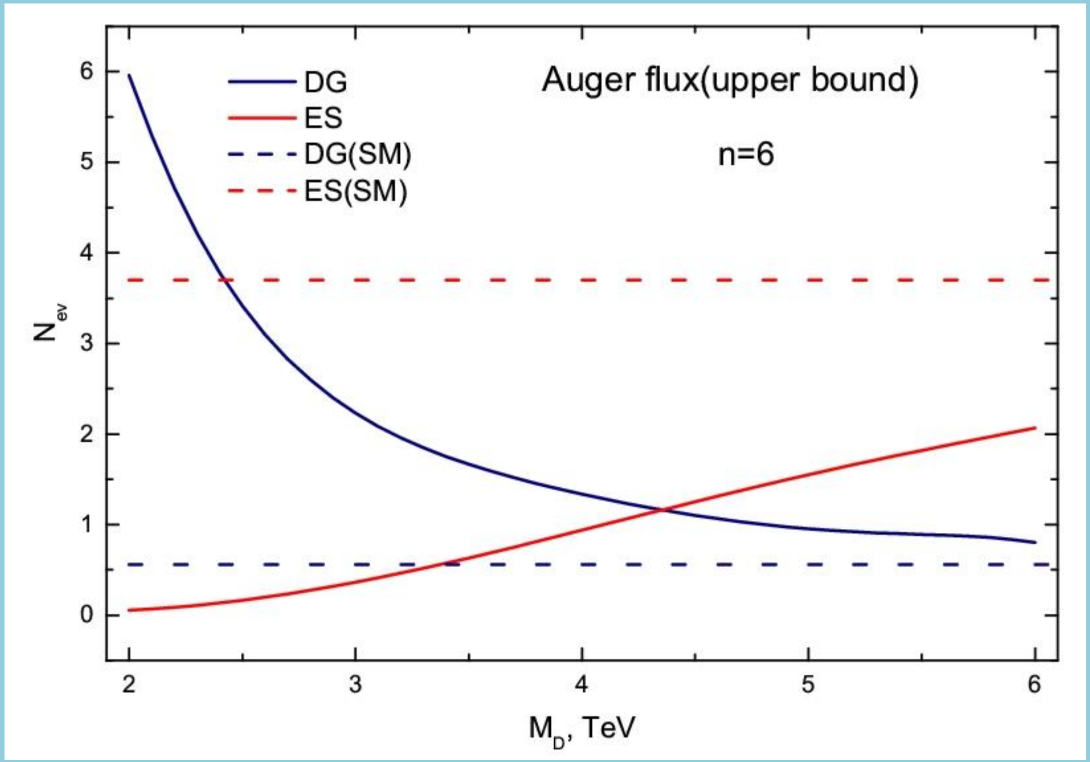




The upper bound on the flux normalizaion **k** in the ADD model as a function of **n** at fixed values of $\mathbf{M_D}$

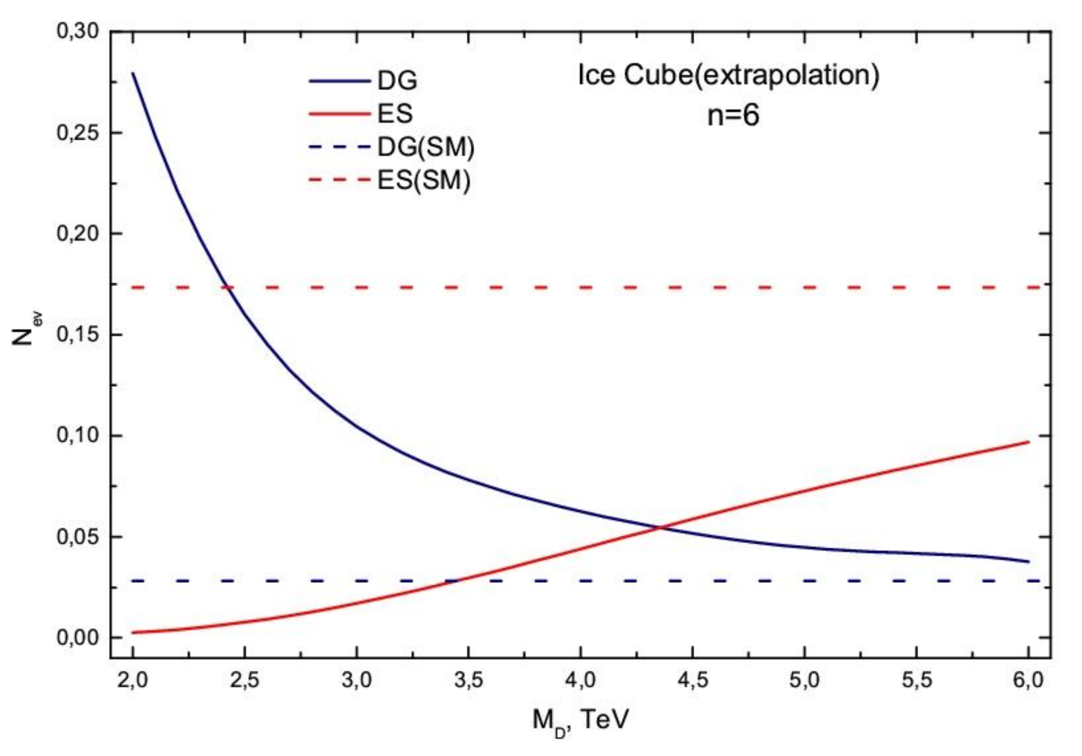
(M. Astashenkov and A. K., arXiv:1804.02351)

Expected number of events induced by UHE neutrinos with the Auger flux



Expected number of neutrino events at the SD of the PAO for a period equivalent of 2•6.4 years of PAO working continuously

Expected number of events induced by UHE neutrinos with the IceCube flux



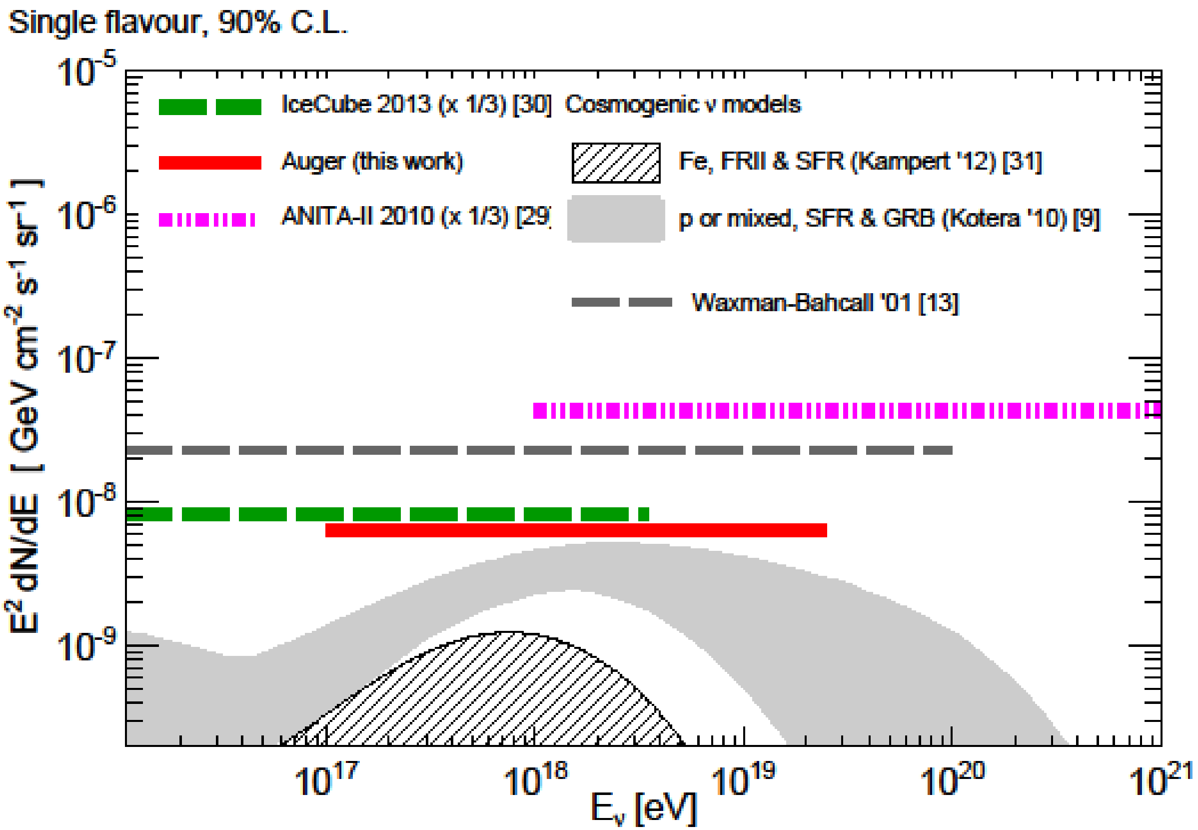
Expected number of neutrino events at the SD of the PAO for a period equivalent of 2•6.4 years of PAO working continuously

Conclusions

- In the scenario with flat EDs the upper limit on the diffuse UHE neutrino flux is calculated as a function of number of extra dimensions n and D-dimensional Planck scale M_D
- This limit turned out to be more stringent than the PAO upper limit for $M_D < 3$ TeV (2.4 TeV), if $n = 2$ (6), as well as for $M_D = 2.3$ TeV, if $n \leq 3$ or $n \geq 6$
- For large values of the gravity scale, $M_D \geq 4$ TeV, our bound, on the contrary, exceeds the PAO bound for all n
- The expected number of DG and ES neutrino events at the PAO is estimated both for the PAO bound and for the IceCube neutrino flux extrapolated to PAO energies (for 2•6.4 years of continuous operation)

Thank you for attention

Back-up slides


Single flavour, 90% C.L.
IceCube 2013 (x 1/3) [30]
Auger (this work)
ANITA-II 2010 (x 1/3) [29]
Cosmogenic ν models
Fe, FRII & SFR (Kampert '12) [31]
p or mixed, SFR & GRB (Kotera '10) [9]
Waxman-Bahcall '01 [13]
E^2 dN/dE [GeV cm^{-2} s^{-1} sr^{-1}]
E_ν [eV]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}

Diffuse flux Neutrino model	Expected number of events (1 January 2004–20 June 2013)	Probability of observing 0
Cosmogenic—proton, FRII [33]	~4.0	$\sim 1.8 \times 10^{-2}$
Cosmogenic—proton, SFR [33]	~0.9	~0.4
Cosmogenic—proton, Fermi-LAT, $E_{min} = 10^{19}$ eV [34]	~3.2	$\sim 4 \times 10^{-2}$
Cosmogenic—proton, Fermi-LAT, $E_{min} = 10^{17.5}$ eV [34]	~1.6	~0.2
Cosmogenic—proton or mixed, SFR & GRB [9]	~0.5–1.4	~0.6–0.2
Cosmogenic—iron, FRII [33]	~0.3	~0.7
Astrophysical ν (AGN) [35]	~7.2	$\sim 7 \times 10^{-4}$
Exotic [36]	~31.5	$\sim 2 \times 10^{-14}$

(PAO Collab., PRD 91 (2015) 092008)

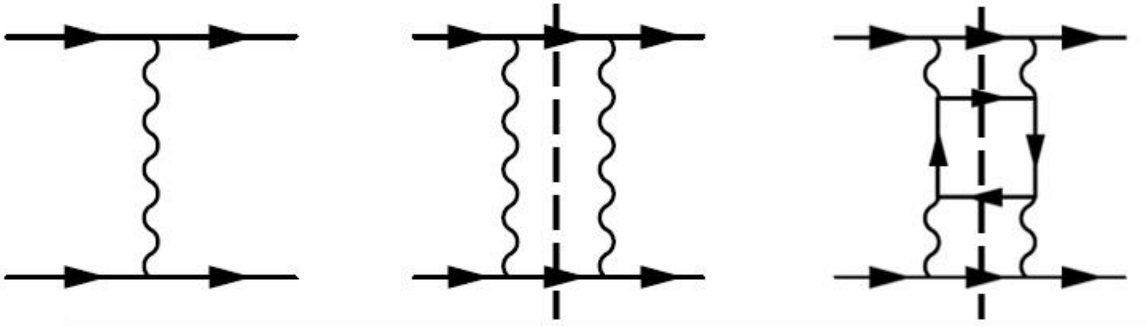
Efficiencies of the SD array depends on:

the neutrino energy E_ν, the incident zenith angle θ and interaction depth in the atmosphere D (DG events), or the altitude h (ES events)

Once efficiencies are obtained, exposure involves:

SD array aperture and ν interaction probability at the depth D, energy E_ν and the search period T (DG events)

SD array aperture, probability density function of tau emerging from the Earth with energy E_τ, probability of tau decaying at the altitude h and the search period T (ES events)

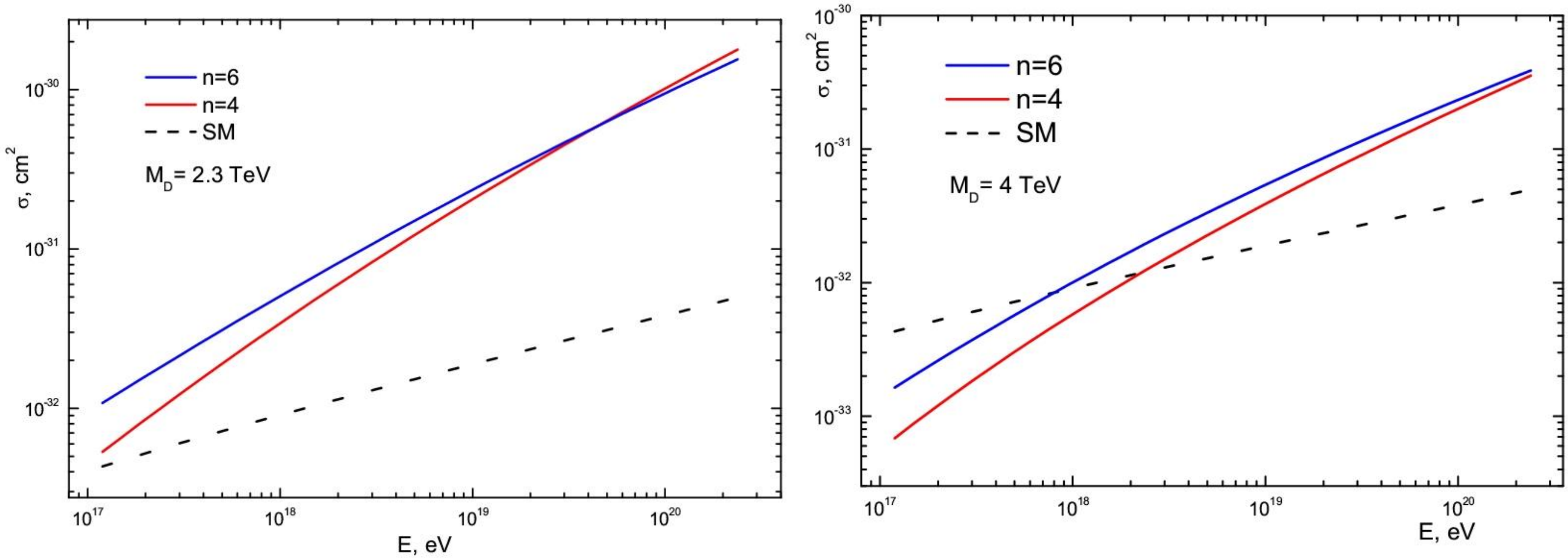


The s^2 dependence of the graviton-exchange Born term renders the sum of exchanges dominant with respect to the inelastic diagrams (see third diagram on this figure)

Ordinary gauge theory:
no classical limit

Different properties of spin-2 and spin-1 exchange –
because energy itself plays the role of charge in gravity

BSM: $\sigma_{\nu N}$ does not significantly depend on n for $n \geq 3$ at high energies



The total neutrino-nucleon cross sections for **M_D = 2.3 TeV** (left panel) and **M_D = 4 TeV** (right panel) with two values of the number of extra dimensions **n**

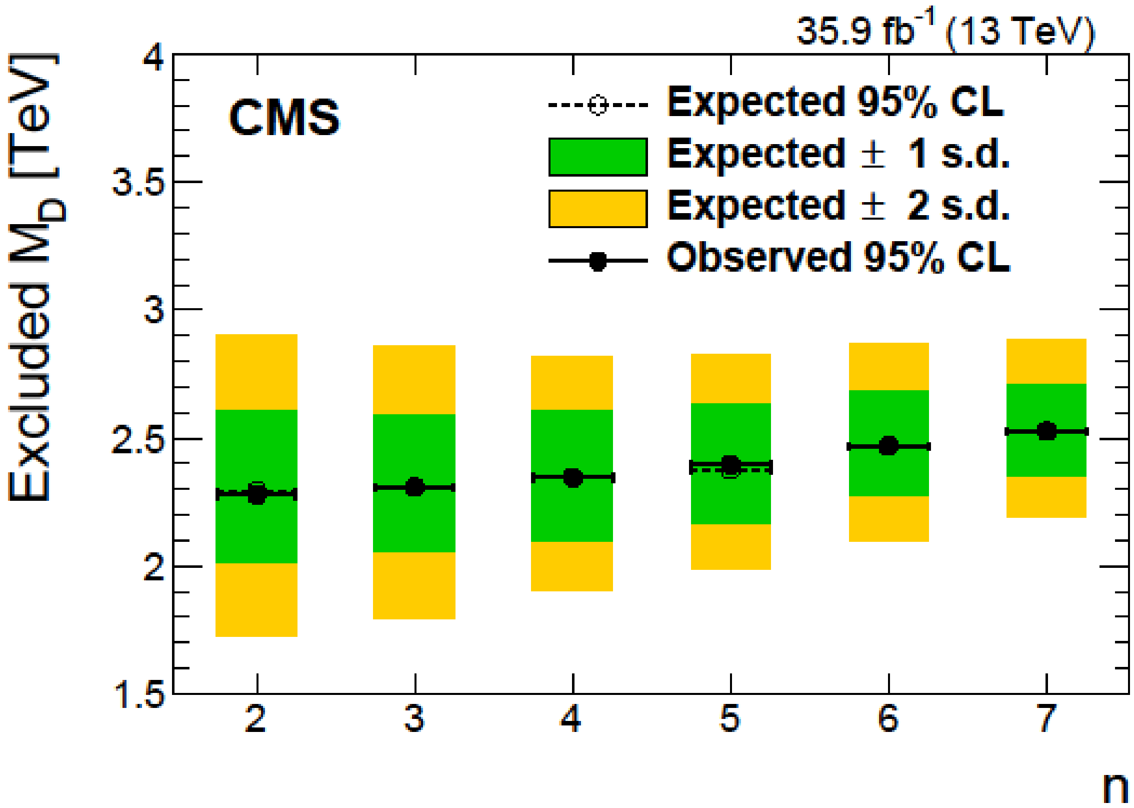
$\log E/\mathrm{eV}$	ν_e CC	ν_μ CC	ν_τ CC	ν_x NC	ν_τ Mount.
16.75	$4.35 \cdot 10^{21}$	$5.27 \cdot 10^{20}$	$1.82 \cdot 10^{21}$	$2.11 \cdot 10^{20}$	-
17	$1.27 \cdot 10^{22}$	$3.16 \cdot 10^{21}$	$1.09 \cdot 10^{22}$	$1.26 \cdot 10^{21}$	-
17.5	$7.94 \cdot 10^{22}$	$2.34 \cdot 10^{22}$	$6.02 \cdot 10^{22}$	$9.37 \cdot 10^{21}$	$1.98 \cdot 10^{22}$
18	$2.17 \cdot 10^{23}$	$8.01 \cdot 10^{22}$	$1.77 \cdot 10^{23}$	$3.20 \cdot 10^{22}$	$1.21 \cdot 10^{23}$
18.5	$3.95 \cdot 10^{23}$	$1.71 \cdot 10^{23}$	$2.84 \cdot 10^{23}$	$6.84 \cdot 10^{22}$	$2.51 \cdot 10^{23}$
19	$5.44 \cdot 10^{23}$	$2.56 \cdot 10^{23}$	$3.58 \cdot 10^{23}$	$1.03 \cdot 10^{23}$	$3.13 \cdot 10^{23}$
19.5	$6.32 \cdot 10^{23}$	$2.99 \cdot 10^{23}$	$4.36 \cdot 10^{23}$	$1.20 \cdot 10^{23}$	$3.06 \cdot 10^{23}$
20	$7.29 \cdot 10^{23}$	$3.45 \cdot 10^{23}$	$5.19 \cdot 10^{23}$	$1.38 \cdot 10^{23}$	$2.82 \cdot 10^{23}$

Effective mass apertures A_i for DG neutrinos of the PAO Surface Detector in units of [g s sr]

(PAO Collab., PRD 84 (2011) 122005)

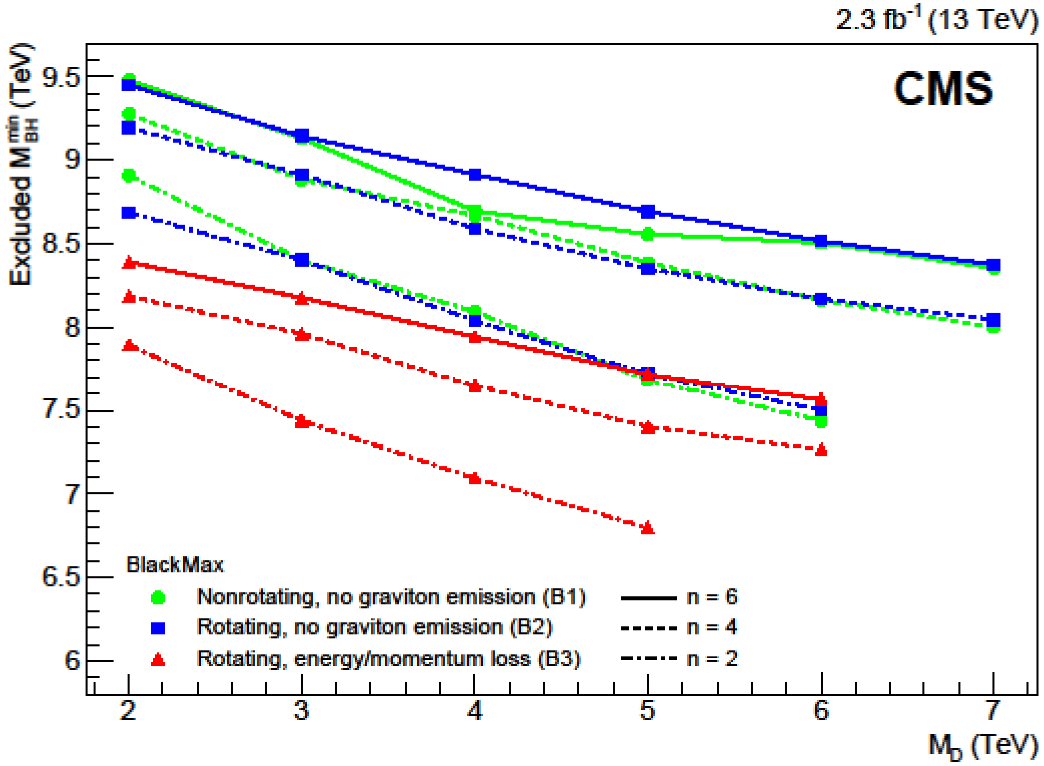
Exposure of the SD for DG neutrinos:

$$E(E_\nu) = \sum_i \sigma_i(E_\nu)\, A_i(E_\nu)/m_N$$



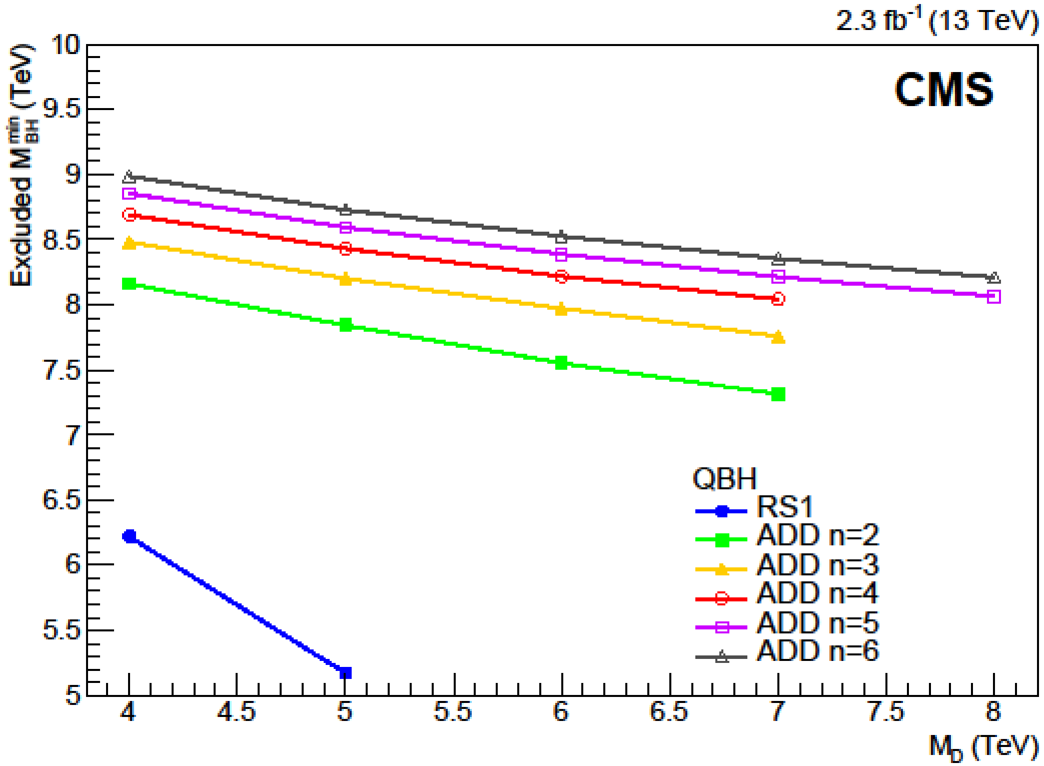
Expected and observed 95% CL exclusion limits on M_D in the ADD scenario for different values of n

(CMS Collab., EPJC 78 (2018) 291)



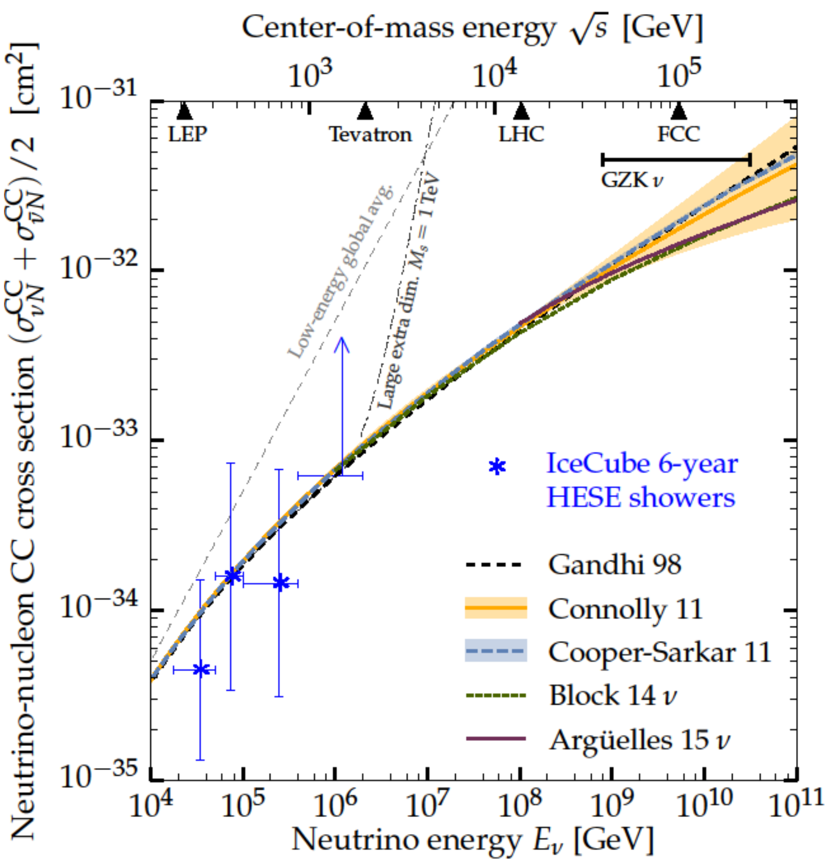
The 95% CL lower limits on minimum semiclassical black hole mass as a function of the Planck scale M_D, for several benchmark models

(CMS Collab., Phys. Lett. D 774 (2017) 279)



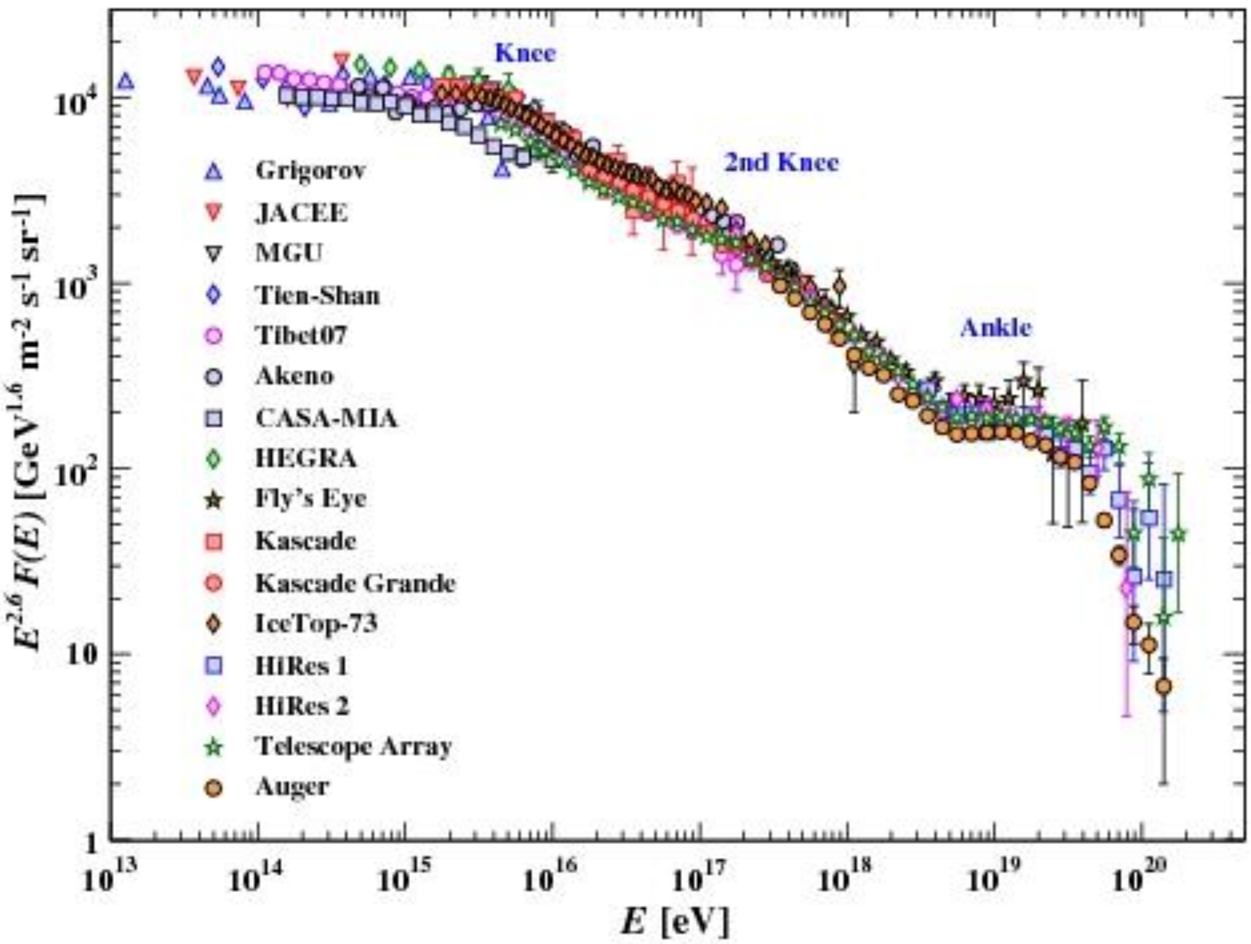
The 95% CL lower limits on minimum quantum black hole mass as a function of the Planck scale M_D, for several benchmark models (bound in the RS1 scenario is also shown)

(CMS Collab., Phys. Lett. D 774 (2017) 279)

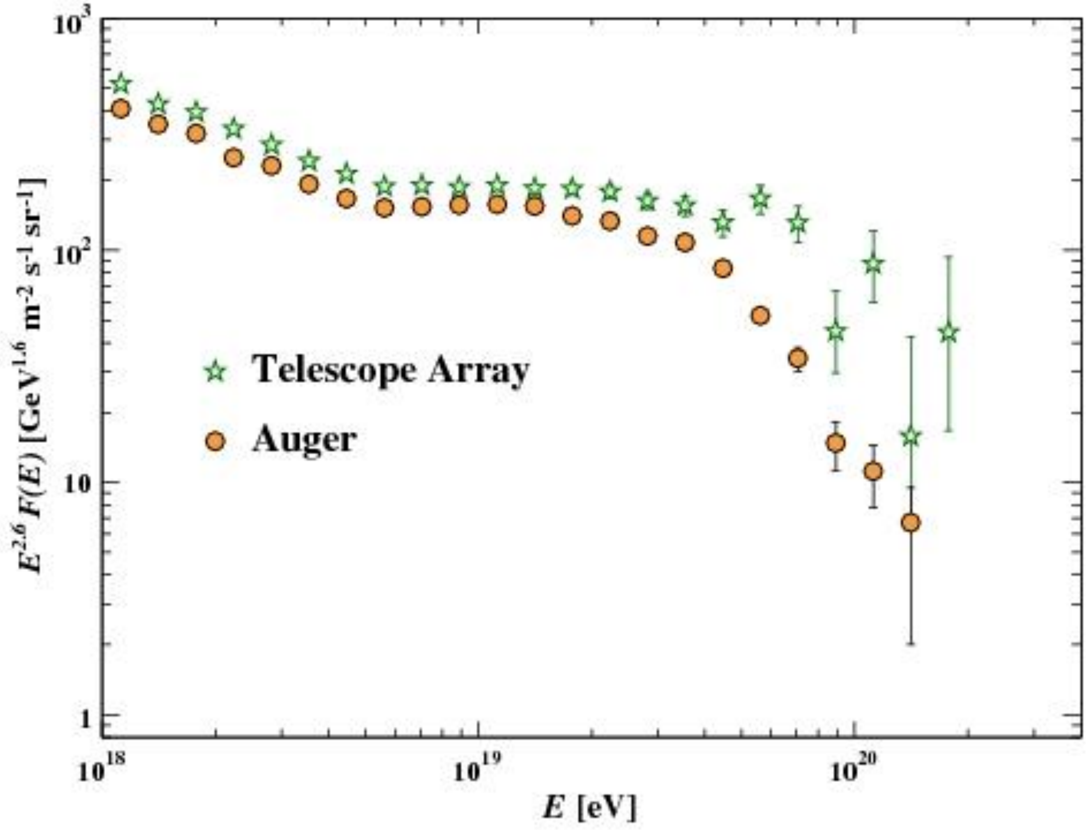


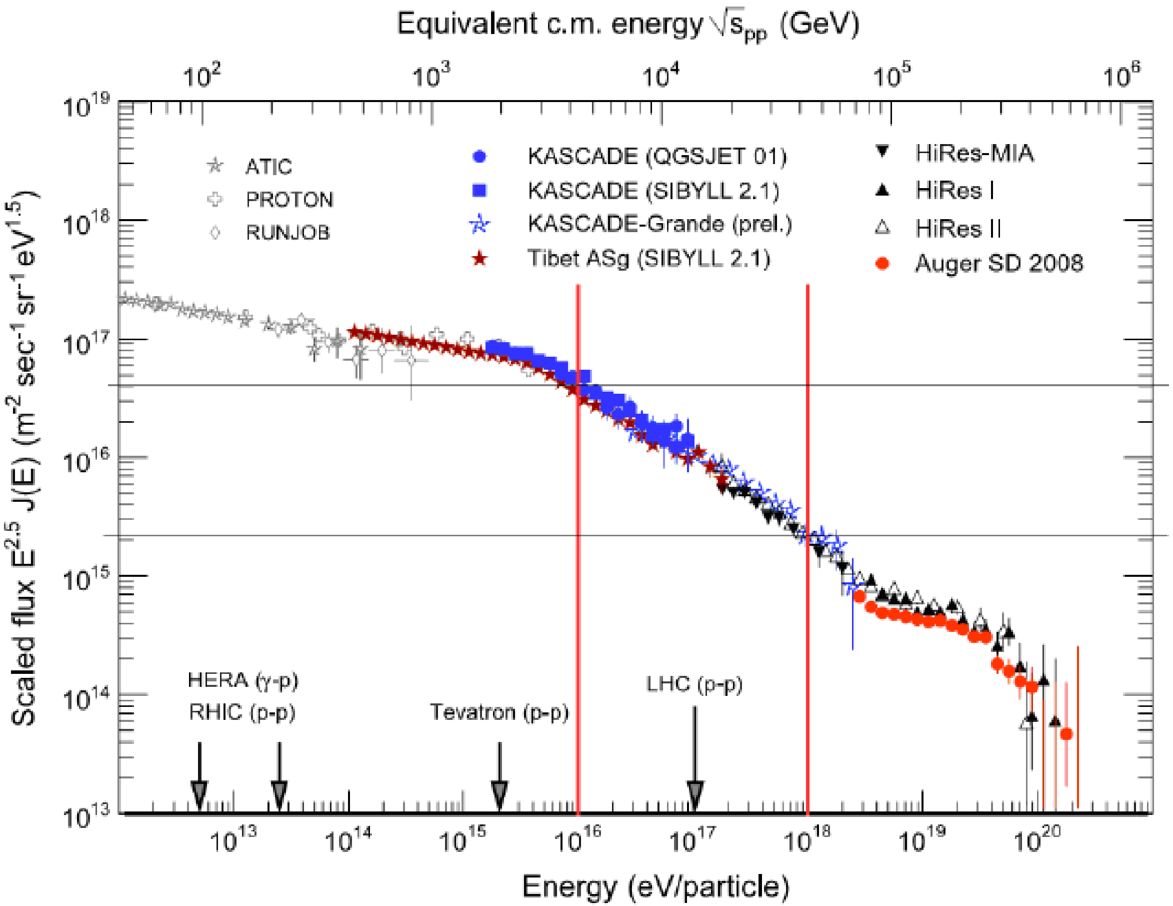
Neutrino-nucleon charged-current cross section, averaged for neutrino and antineutrino, from different predictions

(Bustamante and Connolly, arXiv:1711.11043)

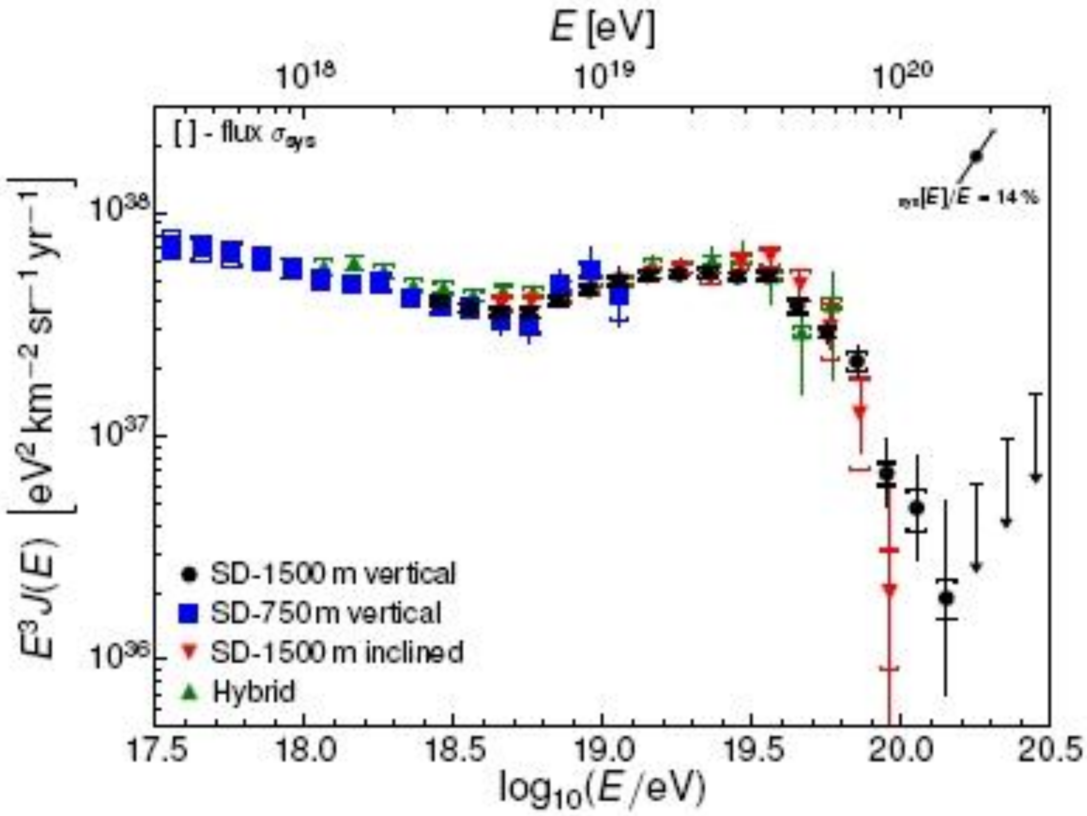


Knee
2nd Knee
Ankle
Grigorov
JACEE
MGU
Tien-Shan
Tibet07
Akeno
CASA-MIA
HEGRA
Fly's Eye
Kascade
Kascade Grande
IceTop-73
HiRes 1
HiRes 2
Telescope Array
Auger
$E^{2.6} F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
E [eV]


Telescope Array
Auger
$E^{2.6} F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
E [eV]
10^3
10^2
10
1
10^{18}
10^{19}
10^{20}

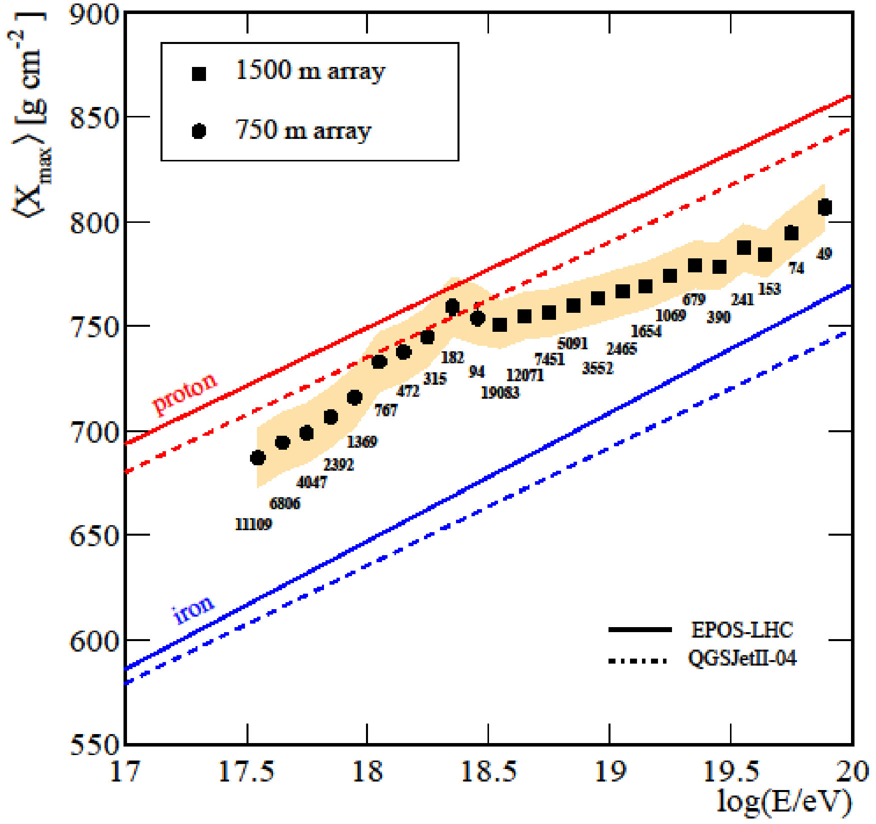


All-particle cosmic-ray energy spectrum



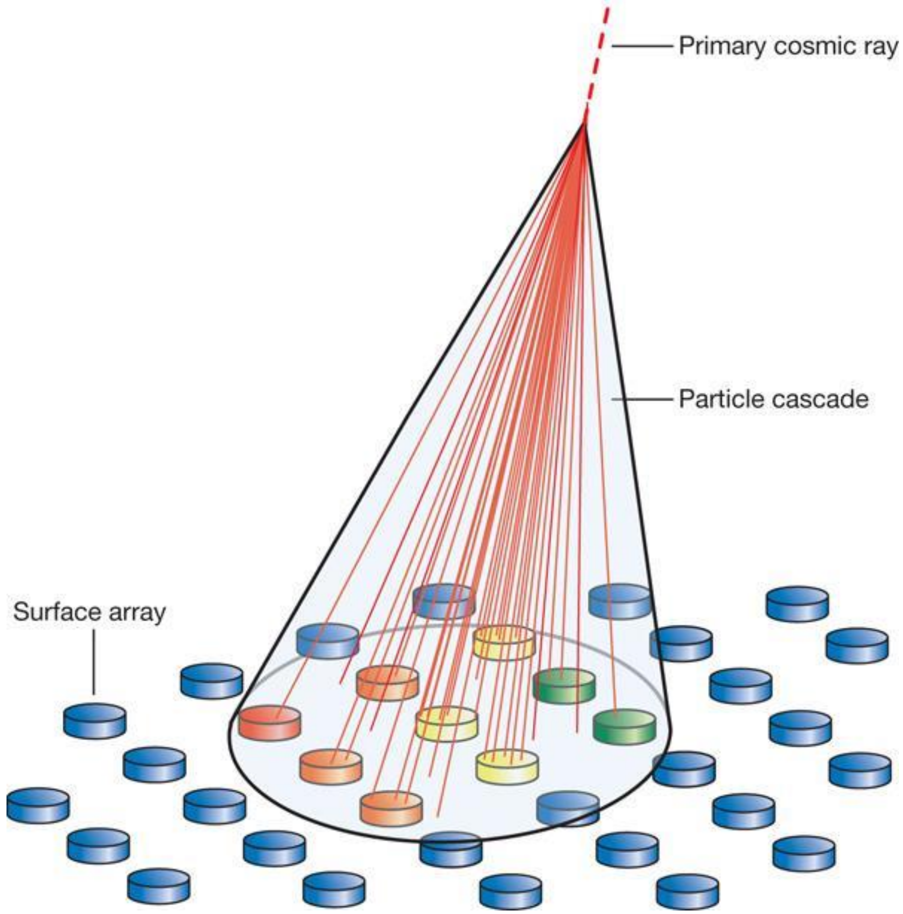
Energy spectrum derived from the Surface detector (SD) and hybrid data at the Pierre Auger Observatory (PAO)

(PAO Collab., ICRC, 2015)

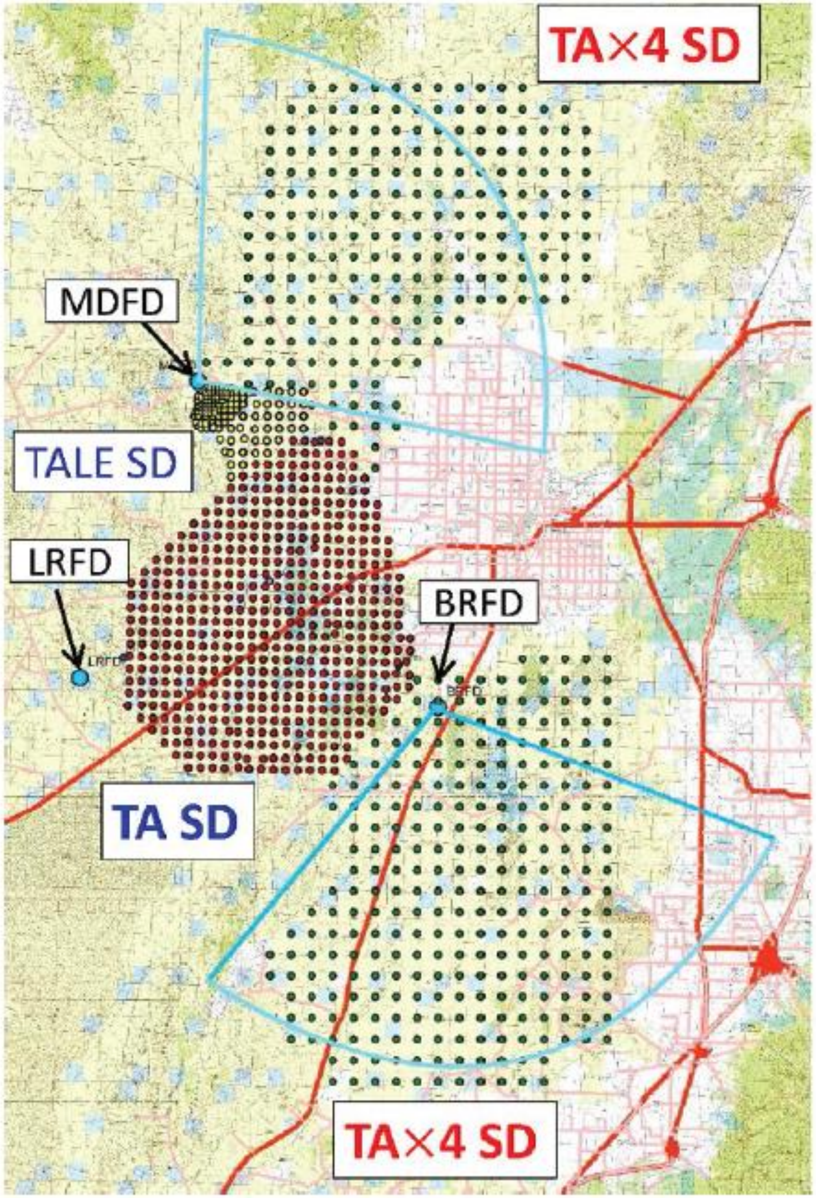


Average depth of shower maxima as a function of energy

(*PAO Collaboration, PRD 96(2017)122003*)



Detection of air showers by the Surface Detector (SD) of the PAO



Lay out of the Telescope Array extension (TA× 4)